# Hydrocarbon exploration in the Austrian Alps

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**ABSTRACT**

Following discovery of several oil and gas accumulations in the allochthonous units underlying the Neogene Vienna Basin and in the autochthonous series of the Molasse foreland basin, exploration for hydrocarbons commenced in the late 1950's also in the Alpine Flysch Zone and the nappes of the Calcareous Alps.

Targets were Mesozoic and Paleogene series covering the sub-thrust authochthonous basement of the European foreland, which dips as a gentle monocline at least 65 km beneath the Alpine nappes, as well as the Mesozoic series involved in these nappes. Autochthonous reservoir rocks comprise Middle Jurassic and Cretaceous sandstones, Late Jurassic carbonates and Eocene and Oligocene sandstones. In analogy with the reservoirs of the oil and gas fields dicovered beneath the Neogene sedimentary fill of the Vienna basin, Triassic dolomites present a potential objective within the nappes of the Calcareous Alps. In the western parts of the Austrian Alps, autochthonous Triassic and Early Jurassic, as well as the allochthonous Mesozoic sediments of the Helvetic nappes present possible targets.

East of the basement spur, which projects from the Bohemian Massif under the Alpine-Carpathian nappes, autochthonous Late Jurassic shales form a major source-rock; west of this spur, basal Oligocene shales have excellent source-rock characteristics. Within the allochthonous units several potential source-rock intervals are recognized. Maturation of source-rocks was achieved during thrust-loaded subsidence caused by the emplacement of the Alpine nappes.

Exploration activity in Alpine Austria includes surface geological mapping, gravity and magnetic surveys and the acquisition of 5000 km of 2D reflection-seismic lines and two 3D surveys. Within the Flysch Zone and the Helveticum 24 and within the Calcareous Alps 8 exploration wells were drilled. The deepest well reached a total depth of 6028 m. In addition a number of wells were drilled in the imbricated sub-Alpine Molasse.

Near Vienna, the large Höflein gas field was discovered in the autochthonous Mesozoic series beneath the Flysch Zone. In Upper Austria, the well Molln-1 tested gas from Triassic carbonates of the Calcareous Alps nappes. Exploration of the Sub-Alpine Molasse yielded the light oil discovery of well Mühlreit-1. Apart from Höflein, all discoveries were subcommercial.

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*This article includes 1 enclosure.*

Exploration in the Alpine belt of Austria has met with only limited succes due to poor structural definition of prospects involving either autochthonous or allochthonous series. In this respect, the complexity of overburden geometries and topographic constraints on recording sufficiently dense reflection-seismic grids played an important role. Although all ingredients for a successful exploration play appear to exist within the Austrian Alpes, the risk/reward ration must be considered as lopsided under todays oil and gas price scenario.

## INTRODUCTION

Austria can look back at a long and successful hydrocarbon exploration history (Brix and Schultz, 1993). The first commercial oil discovery was made 1934 with the drilling of well Gösting-2 in the Neogene Vienna Basin. In 1949 the very large Matzen oil field was found in the same basin; this field remained for a long time the largest oil accumulation found in Europe. In 1959 the first gas accumulation was found in fractured Triassic carbonates, involved in the nappes of the Calcareous Alps, forming the substratum of the Vienna Basin; this discovery was followed by a number of additional oil and gas discoveries in similar reservoirs and tectonic setting. Exploration of the Molasse Basin commenced in the mid 1950's and was rewarded in 1956 with a first oil discovery in Upper Austria and in 1960 with a gas discovery in Lower Austria. By now remaining recoverable reserves in established accumulations of Austria amount to $14.5 \cdot 10^6$ t of oil and condensate ($10^7 \cdot 106$ bbls) and $19.6 \cdot 10^9$ $m^3$ gas (0.73 TCF). Oil production peaked in 1955 with 3.7 t/year ($23 \cdot 10^6$ bbls/year) and gas production in 1978 with $2 \cdot 10^9$ $m^3$/year (73 BCF/year). In 1994 total oil and condensate production amounted to $1.2 \cdot 10^6$ t and total gas production to $1.5 \cdot 10^9$ $m^3$. Both oil and gas production are presently slightly declining.

Following the exploration successes in the Molasse Basin and the substratum of the Vienna Basin, interest in exploration of the Austrian Alps gradually increased during the late 1950's. Initial exploration efforts were directed at the autochthonous Mesozoic and Paleogene strata but later also at the series of the Calcareous Alps. In 1959 the well Texing-1 was the first well which spudded in the Flysch Zone and reached the autochthonous Molasse. In 1966 the first well drilled in the Calcareous Alps, Urmannsau-1, was located in a tectonic window in the vicinity of an oil seep and bottomed at 3033 m in the autochthonous Molasse. Both wells failed to discover hydrocarbons but were in so far important as they proved that the Calcareous Alps, Flysch, Klippenbelt and Helvetic Zone were thrusted over autochthonous Tertiary and Mesozoic sediments covering the gently southwards dipping basement of the foreland. By now 32 exploration wells (Fig. 1) and 10 production wells (gas-condensate field Höflein) have been drilled in the Alpine allochthon; additional wells are located in the imbricated Sub-Alpine Molasses.

## GEOLOGICAL SETTING

Figure 1 provides an overview of the structural framework of Alpine Austria and its foreland. The Calcareous Alps (Kalkalpen), forming the orogenic lid of the Alpine stack of nappes, consist of the lower, middle and upper Austroalpine nappes; these were derived from the southern margin of the South Pennininc trough. During the Cretaceous gradual closure of the Alpine Tethys, these nappes were transported northwestwards (Ring et al., 1989; Eisbacher et al., 1990; Froitzheim et al., 1994; Neubauer, 1994). During the Senonian and Paleocene, increasing collisional coupling between the rising Alpine orogen and its European foreland is reflected by compressional deformation of the latter, resulting in basin inversion and upthrusting of basement blocks forming the Bohemian Massif (Ziegler, 1990). During the Paleogene, the Austroalpine nappes, together with the Pennininc and Helvetic nappes, advanced northwards and overrode the European foreland (Ratschbacher et al., 1991), causing the flexural subsidence of the Molasse Basin. By late Oligocene-early Miocene

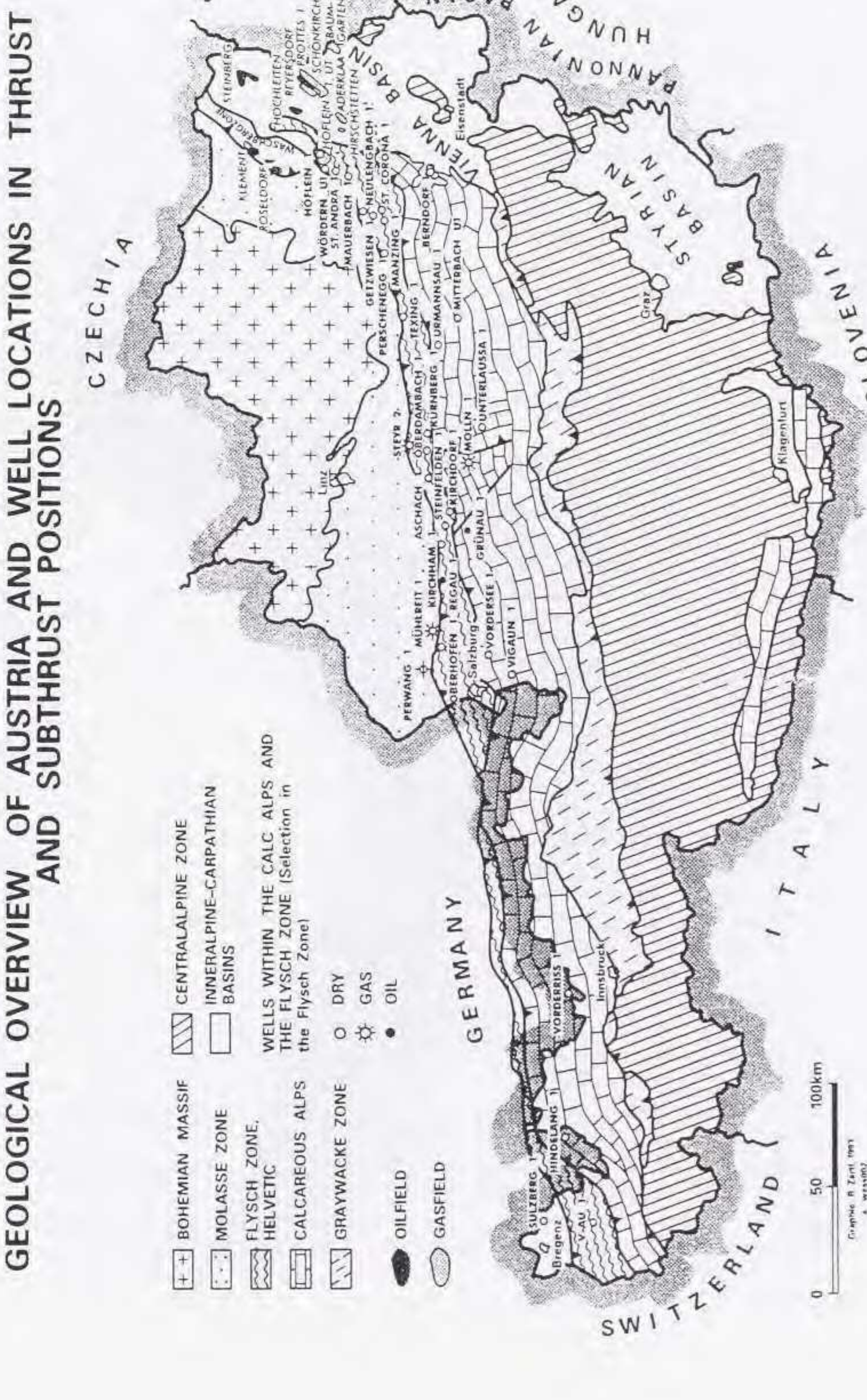

GEOLOGICAL OVERVIEW OF AUSTRIA AND WELL LOCATIONS IN THRUST AND SUBTHRUST POSITIONS
BOHEMIAN MASSIF
MOLASSE ZONE
FLYSCH ZONE, HELVETIC
CALCAREOUS ALPS
GRAYWACKE ZONE
CENTRALALPINE ZONE
INNERALPINE-CARPATHIAN BASINS
WELLS WITHIN THE CALC ALPS AND THE FLYSCH ZONE (Selection in the Flysch Zone)
DRY
GAS
OIL
OILFIELD
GASFIELD
CZECHIA
SLOVAKIA
VIENNA BASIN
PANNONIAN BASIN
HUNGARY
STYRIAN BASIN
SLOVENIA
ITALY
SWITZERLAND
GERMANY
Linz
Salzburg
Innsbruck
Graz
Klagenfurt
Bregenz
Eisenstadt
0
50
100km

FIG. 1.

times, the entire nappe system was emplaced near its present position. While thrust activity persisted into late Miocene times in Lower Austria, early Miocene series seal the thrust front in Upper Austria. Results of deep exploration wells and reflection seismic data show that the European foreland crust dips gently southwards under the Alpine nappes and extends at least 65 km to the south of the present Alpine thrust front (Encl. 1).

Hydrocarbon exploration in Alpine Austria is restricted to the Calcareous Alps, the Flysch and Helvetic Zones and the sub-Alpine Molasse. Potential prospects occur in the the sub-thrust autochthonous units and within the allochthonous units.

## Autochthonous Plays

The hydrocarbon habitat in autochthonous sub-thrust sedimentary series can be extrapolated from the updip, northward adjacent Molasse Basin in which a large number of oil and gas fields has been established. These produce variably from Jurassic sandstones and carbonates, Cretaceous and Eocene sands and Oligocene and early Miocene sands of the Molasse sequence (Fig. 7; Kollmann and Malzer, 1980; Kröll, 1980a).

Productive structures, involving Eocene and older reservoirs, are controlled by antithetic and to a lesser degree by synthetic normal faults; these developed during the Oligocene thrust-loaded rapid subsidence of the Alpine foreland. Such faults have generally throws of the order of 100 to 300 m. There are occasional examples of Oligocene extensional faults which were compressionally reactivated during the late phases of the Alpine orogeny. Only the well Perwang-1 encountered imbrications of Eocene and Late Cretaceous autochthonous series. Traps controlled by pre-Tertiary faults play a subordinate role. Oil and oil/gas accumulations are essentially restricted to Eocene and older reservoirs. Oligocene and Miocene sands contain in stratigraphic and differential compaction structures biogenic gas.

Along the strike of the Molasse Basin, the thickness and composition of Mesozoic and Paleogene strata varies considerably. This can be attributed mainly to the basal onlap geometry of Mesozoic strata against the Variscan basement, the regional base-Cretaceous and basal Tertiary unconformities, and the onlap geometry of the Eocene and Oligocene sediments against the palaeo-relief of the basal Tertiary erosional surface. These lateral variations have a strong bearing on the availability of reservoirs and source-rocks (Figs. 2 and 3).

West of Vienna, a spur of the Bohemian Massif projects deeply under the Alpine nappes. In this area transgressive Oligocene sands and shales rest directly on basement. The southwestern flank of this palaeo-high is controlled by a major fault (Steyer fault).

To the east of this spur, Permo-Carboniferous clastics are unconformably overlain by Middle Jurassic paralic and deltaic sands, involved in rotational, extensional fault blocks (Fig. 3). These are sealed by Late Jurassic carbonates which grade laterally into basinal shales having an excellent source-rock potential (Ladwein, 1988). The Jurassic sequence, which terminates with regressive Tithonian carbonates, attains thicknesses of up to 2000 m. It is regionally truncated by an Early Cretaceous unconformity which is related to wrench-deformations of the Bohemian Massif. Late Cretaceous sands carbonates and marls, up to 900 m thick, are truncated by a second regional unconformity which is related to compressional deformations of the Bohemian Massif during early Paleocene times. Oligocene transgressive sands overstep this erosional surface and are in turn overlain by a Miocene shaly sequence. Jurassic carbonates and sands form the reservoirs of several oil and gas accumulations. Oligocene and Miocene sands contain biogenic gas accumulations (Brix et al., 1977; Kröll, 1980a; Wessely, 1987).

To the west of the Bohemian basement spur, thin Middle Jurassic sands rest on basement and are conformably overlain by Late Jurassic carbonates attaining maximum thicknesses of some 750 m (Fig. 3). Rapid lateral thickness changes are controlled by the basal Cretaceous unconformity and associated faulting. Local porosity developments are related to fracturing and karstification of the partly reefal Jurassic carbonates. Sedimentation resumed with the transgression of Apto-Albian marine sands. Cenomanian glauconitic sands attain thicknesses of 75 m and form, together with Middle Jurassic sands, the deeper reservoir of the

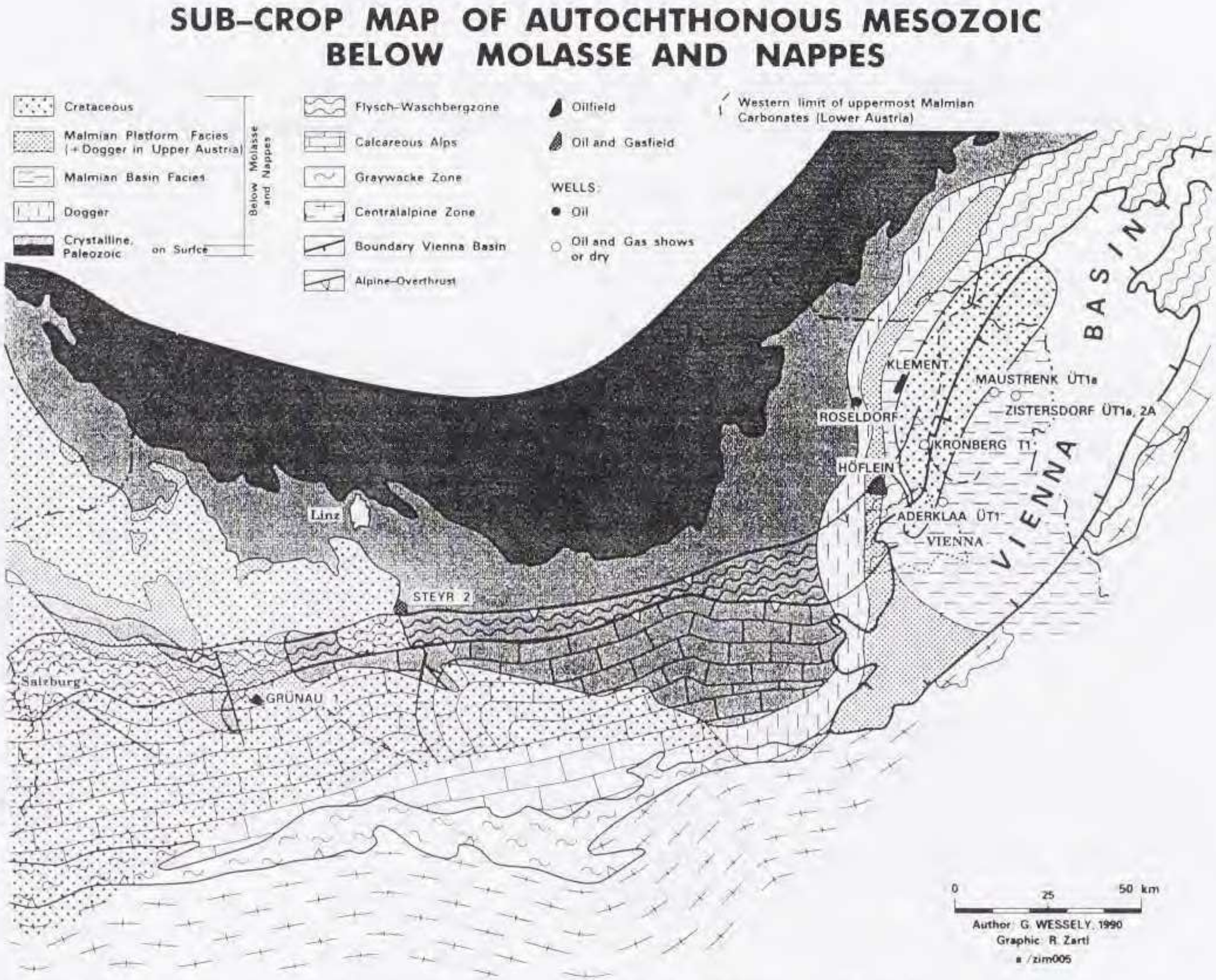
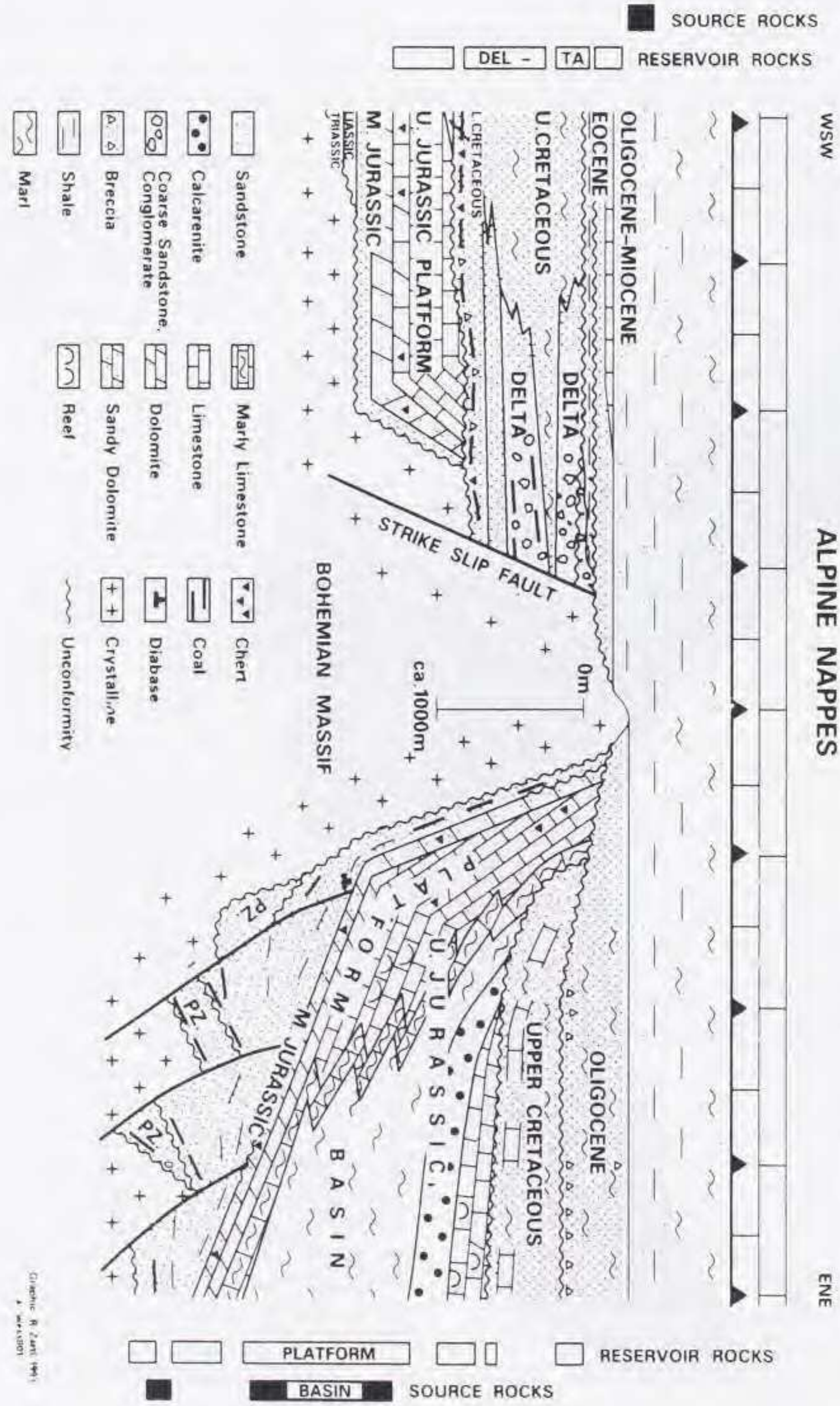



FIG. 2. The subcrop pattern of Mesozoic and older series beneath the base-Tertiary unconformity bears no relationship with the strike of the Alpine nappe systems. The map is closely constrained by wells and seimic data in the Molasse Basin and becomes progressively more hypothetical under the Calcareous Alps.


STRATIGRAPHIC SCHEME OF THE AUTOCHTHOUNS MESOZOIC AND MOLASSE COVERING THE SOUTHERN BOHEMIAN MASSF
WSW
ENE
ALPINE NAPPES
SOURCE ROCKS
DEL -
TA
RESERVOIR ROCKS
OLIGOCENE-MIOCENE
EOCENE
U.CRETACEOUS
L.CRETACEOUS
U. JURASSIC PLATFORM
M. JURASSIC
LIASSIC
TRIASSIC
DELTA
DELTA
STRIKE SLIP FAULT
BOHEMIAN MASSIF
0m
ca.1000m
OLIGOCENE
UPPER CRETACEOUS
U. JURASSIC
PLATFORM
M. JURASSIC
BASIN
PZ
PLATFORM
RESERVOIR ROCKS
BASIN
SOURCE ROCKS
Sandstone
Calcarenite
Coarse Sandstone, Conglomerate
Breccia
Shale
Marl
Marly Limestone
Limestone
Dolomite
Sandy Dolomite
Reef
Chert
Coal
Diabase
Crystalline
Unconformity
FIG. 3.

Voitsdorf field which is the largest oil accumulation of Upper Austria. These sands are capped by Turonian and Senonian clays which grade towards the Bohemian basement spur upwards into sands derived from the Bohemian Massif. Late Cretaceous sediments reach maximum thicknesses of about 1000 m. Transpressional deformations during the Paleocene resulted in a profound disruption of the Late Cretaceous shelf series and in erosion cutting locally down through Jurassic series into the basement. During the late Eocene, the Early Tertiary erosional surface was overstepped by fluvial and shallow marine sands which grade upwards into Lithothamnimum limestones. These Eocene sands form an important reservoir for oil accumulations. Rapid deepening of the area at the transition from the Eocene to the Oligocene was accompanied by the deposition of the highly organic Fish-shales, which constitute the primary source-rock for the oil accumulations of Upper Austria and Salzburg and the adjacent area of Bavaria . This rapid deepening phase was accompanied by the development on an array of essentially basin-parallel, trap-providing antithetic and synthetic normal faults. During the Oligocene, influx of coarse clastics from the advancing Alpine nappe system gave rise to the accumulation of the turbiditic Puchkirchen conglomerate and sand fans. Their southern parts were overridden during the latest Oligocene-early Miocene emplacement of the Alpine nappes, resulting in a narrowing of the Molasse basin. The middle and late Miocene Hall and Innviertel series were deposited under upwards shallowing conditions. Deep-water sands of the Puchkirchen and Hall series are charges by biogenic gas that is essentially stratigraphically trapped (Kollmann and Malzer, 1980; Polesny, 1983; Nachtmann and Wagner, 1987).

In the western parts of the German Molasse Basin, the Variscan basement is overlain by Triassic sediments, a complete sequence of Early and Middle Jurassic strata and progressively northwards truncated Late Jurassic carbonates. Cretaceous sediments have a limited distribution in the eastern part of the Bavarian Molasse basin but are thought to be more widespread under the Alpine nappes. The effects of the basal Cretaceous and Paleogene unconformities appear to be less intense than in the Austrian Molasse Basin. Although occurrence of the transgressive late Eocene sands and Lithothaminium limestones is restricted to the southern parts of the Bavarian Molasse Basin, these are likely to be present in the autochthon of the Alpine nappes. The same applies for the early Oligocene Fish-shales source-rock. Additional potential source-rocks are likely to occur in Middle Triassic carbonates and the pelagic facies to Late Jurassic carbonates (Bachmann et al., 1987; Bachmann and Müller, 1991; Bachmann and Roeder, this volume).

The subcop pattern of Mesozoic strata beneath the basal Tertiary unconformity (Fig. 2) illustrates that also in a subthrust position the distribution of both reservoir and source-rocks is highly variable. This pertains also to the distribution of Eocene reservoirs and the basal Oligocene source-rock, as illustrated by the results of the well Berndorf-1 which drilled through the nappes of the Calcareous Alps, 40 km south of the Alpine thrust front, and bottomed at 6028 m in Variscan basement after penetrating a 35 m thick autochthonous Oligocene conglomerate (Encl. 1; Wachtel and Wessely, 1981). On the other hand, rapid lateral changes can be expected across Early Cretaceous and Paleocene faults, as evident by the results of the wells Molln-1 and Grünau-1, drilled 35 km apart (Fig. 4).

Oligocene source-rocks attain maturity for oil generation beneath the frontal parts of the Alpine nappes and probably enter the gas window beneath the internal parts of the Calcareous Alps. With increasing overburden, clastic reservoirs loose their porosities. Correspondingly, the sub-thrust play has to contend with major reservoir and source rock prediction uncertainties. Potential sub-thrust traps are fault-bounded blocks having similar dimensions as in the Molasse Basin, possible compressionally reactivated Oligocene tensional structures and broad arches (Encl. 1).

## Allochthonous Plays

In the Eastern Alps, the wegde-shaped Alpine system of nappes (Fig. 5) was thrusted by at least 100 km over the autochthonous floor, formed by the European foreland (Fig. 6). The complex structure and stratigraphy of these nappes resulted from multiple deformation phases, spanning Jurassic to

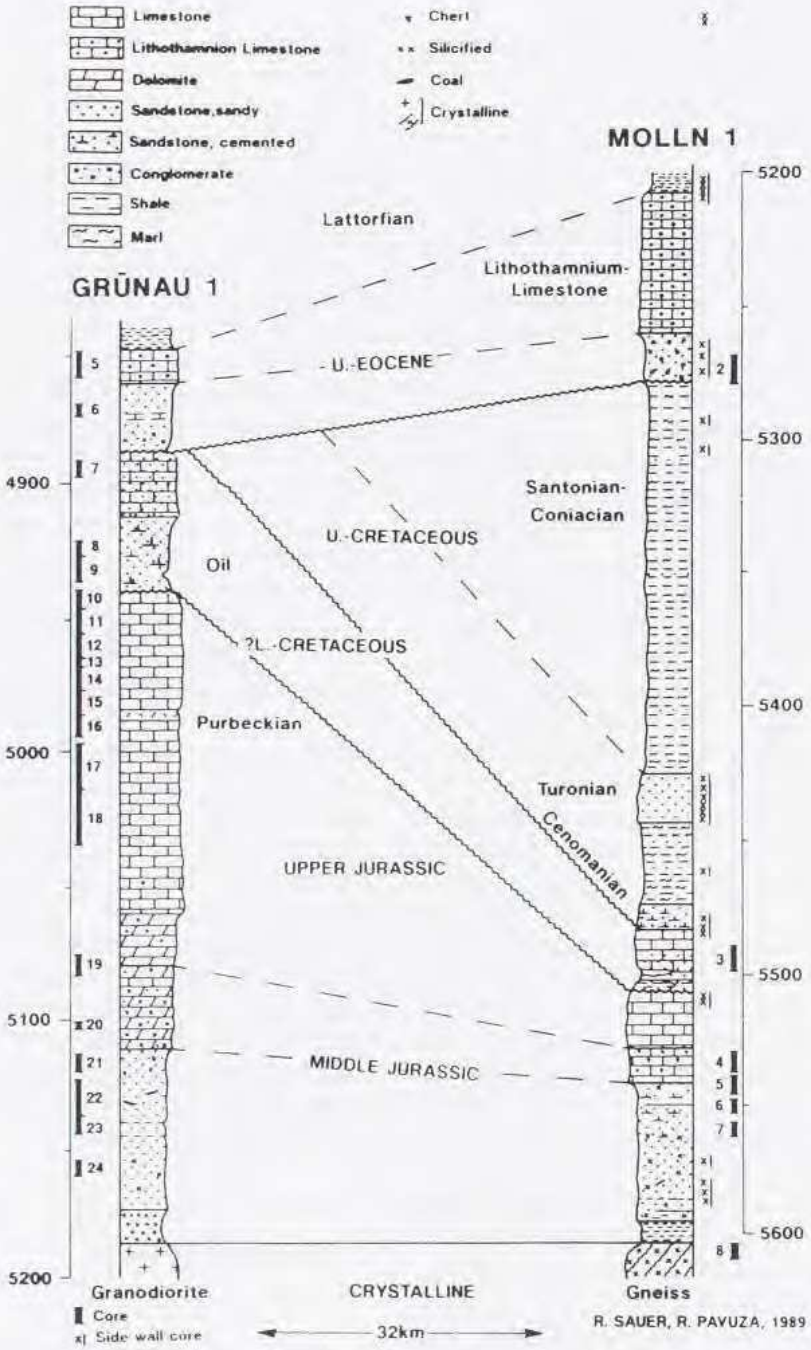



FIG. 4. Correlation of Mesozoic and basal Tertiary series penetrated by wells Grünau-1 and Molln-1, showing effects of base-Cretaceous and Paleocene foreland tectonics.

early Miocene times. These include Triassic to Early Cretaceous rifting events, culminating in the opening of oceanic basins, followed by the onset of subduction processes during the Neocomian and the Late Cretaceous collision of the Alpine orogenic wedge with the European foreland (Tollmann, 1973; Flügel and Faupl, 1987). Collision of the African and European plates controlled the emplacement of the Alpine nappe systems and contemporaneous deformation of the Alpine foreland far to the north of the Alpine thrust front (Ziegler, 1987).

Remnants of the European passive margin sedimentary prism are represented by the Helvetic and the Klippen zones (Fig. 5). The Penninic zone, corresponding to the central Tethyan region, outcrops mainly in the Western and Central Alps and is exposed in the Eastern Alps only in the Unterengadin, Tauern and Rechnitz windows. This zone comprises Palaeozoic to Mesozoic and Paleocene metasedimentary and crystalline rocks, as well as slices the oceanic crust which had formed during the Jurassic and Cretaceous opening of the Tethys (Janoschek and Matura, 1980). The Fysch Zone, which forms part of the Penninic domain, outcrops in a band paralleling the Alpine deformation front.

The Austoalpine nappes were derived from domains located to the south of the Penninic zone, corresponding to the Italo-Dinarid block (Frisch, 1979; Ziegler et al., this volume). They consist of crystalline basement and its Palaeozoic and Mesozoic sedimentary cover. The Lower and Middle Austoalpine units formed, palinspastically speaking, the southern margin of the Penninic zone and are characterized by a very low-grade metamorphic Permo-Mesozoic facies belt. Further to the south, the Upper Austoalpine units include the sedimentary sequences of the Palaeozoic Grauwacken Zone and the unmetamorphosed Permo-Mesozoic and Paleogene sediments of the Calcareous Alps.

During the Cretaceous phases of the Alpine orogeny, the Austroalpine nappes developed and during the Paleogene they moved across the Penninic zone. The Upper Austroalpine nappes of the Calcaresous Alps and the Grauwacken Zone overrode the Lower and Middle Austroalpine nappes and now rest rootless on them and the Penninic flysch. During the Oligocene and early Miocene the entire stack of nappes advance further to the north and was thrusted over the southern, proximal parts of the Molasse foreland basin.

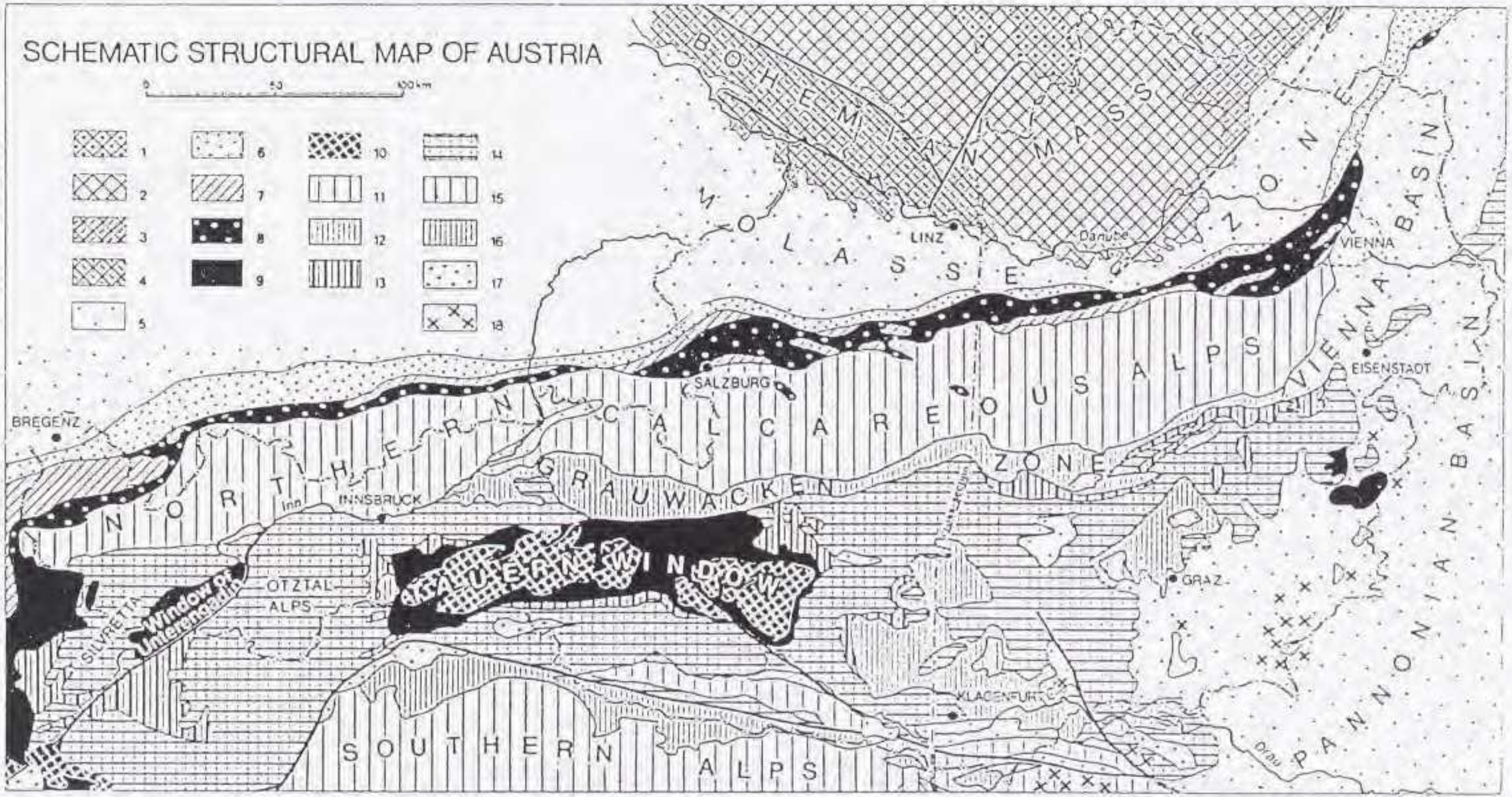
Exploration for hydrocarbons is concentrated on the deformed zone of the Molasse Basin as well as on the allochthonous Helvetic, Flysch and Calacreous Alps zones.

The stratigraphy of the Calcareous Alpine nappes, largely derived from outcrops, shows major vertical and lateral variations. Nevertheless, long-distance facies trends can be established for the main tectono-stratigraphic units of the Calcareous Alps, corresponding to the Bajuvaricum, Tirolicum and Juvavicum, and the Flysch and Helvetic zones (Fig. 7).

Nappes of the Calcareous Alps involve a sedimentary sequence ranging in age from Permo-Scythian to Paleocene. Middle and Late Triassic platform carbonates attain thicknesses in the order of several 1000 m. Late Triassic series are characterized by lateral changes from lagoonal to reefal carbonates and basinal facies partly having source-rock characteristics. Jurassic series are dominated by platform carbonates and basinal shales and carbonates. Cretaceous to Paleogene strata are dominantly developed in a clastic facies.

The fractured Middle and Late Triassic Wetterstein and Hauptdolomite, having low matrix porosities, present potential reservoirs. Limestones constitute neither reservoirs nor seals. Potential seals are provided by Permo-Scythian shales and evaporites, shales and tight sandstones of the Late Triassic Lunz formation and particularly by the Cretaceous to Paleocene Gosau group. Basinal shales and carbonates of Middle Triassic, Rhaetian and Early Jurassic age are partly characterized by elevated TOC values. Maturation of these potential source-rocks depends on their position within the nappe stack but is generally insufficient for the generation of oils.

In the Flysch Zone of the Austrian Alps, to date no hydrocarbon accumulations have been found, mainly due to a lack of porosity. In the western Helvetic Zone, reservoir development can be expected in Middle Jurassic sandstones, the Late Jurassic Quinten Limestone (Müller, 1985a and 1985b) and the Early Cretaceous Schratten Limestone, provided they were intensely enough fractured during tectonic deformation (Müller et al., 1992).

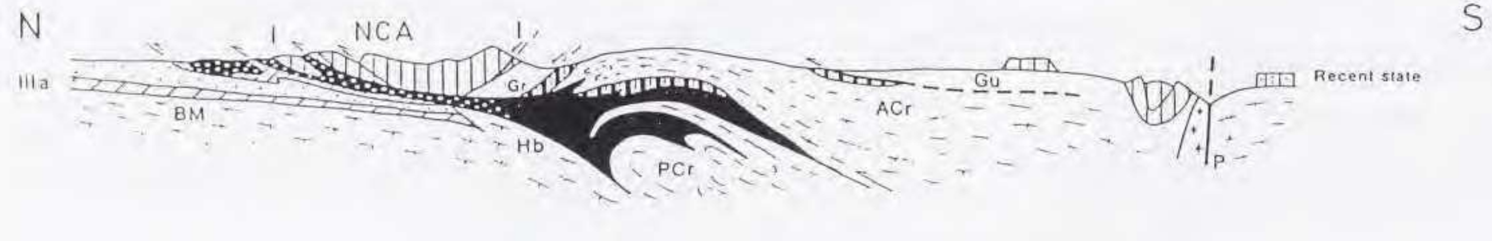


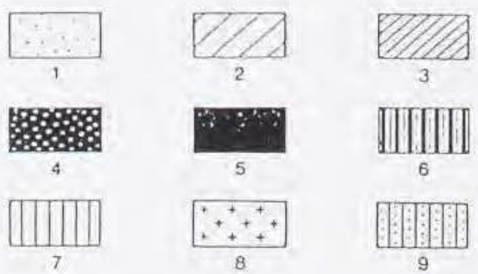

W. JANOSCHEK, A. MATURA 1980

1-4 = Bohemian Massif: 1 = Post - Variscan sedimentary cover; 2 = Moldanubian Zone; 3 = Moravian Zone; 4 = Bavarian Zone; 5 = Tertiary basins; 6 = Subalpine Molasse; 7 = Helvetic and Klippen Zone; 8 = Flysch Zone; 9 = Metasedimentary rocks of the Penninic Zone; 10 = Crystalline basement of the Penninic Zone; 11-14 – Austro - Alpine Unit; 11 = Permomesozoic in Kalk - Alpine facies; 12 = Palaeozoic; 13 = Permomesozoic in Central Alpine facies; 14 = Crystalline basement ("Altkristallin"); 15 = Permomesozoic of the Southern Alps; 16 = Palaeozoic of the Southern Alps; 17 = Periadriatic intrusive masses; 18 = Neogene andesites and basalts.

FIG. 5.

# SCHEMATIC CROSS - SECTION THROUGH THE EASTERN ALPS




1 = Tertiary rocks of the Molasse Zone; 2 = Extra - Alpine post - Variscan sedimentary rocks; 3 = Helvetic Zone and Klippen Zone; 4 = Flysch Zone; 5 = Permomesozoic of the Penninic Zone; 6 = Permomesozoic of the Central - Alpine facies belt; 7 = Permomesozoic of the Kalk - Alpine facies belt; 8 = Periadriatic Intrusion; 9 = South Alpine facies; BM = Bohemian Massif; Hb = Basement of the Helvetic Zone; PCr = Crystalline Basement of the Penninic Zone; Gr = Palaeozoic rocks of the Grauwackenzone; Gu = Palaeozoic rocks of the Gurktal Sheet; ACr = Crystalline basement of the Austro - Alpine Unit; P = Periadriatic Lineament.

FIG. 6.

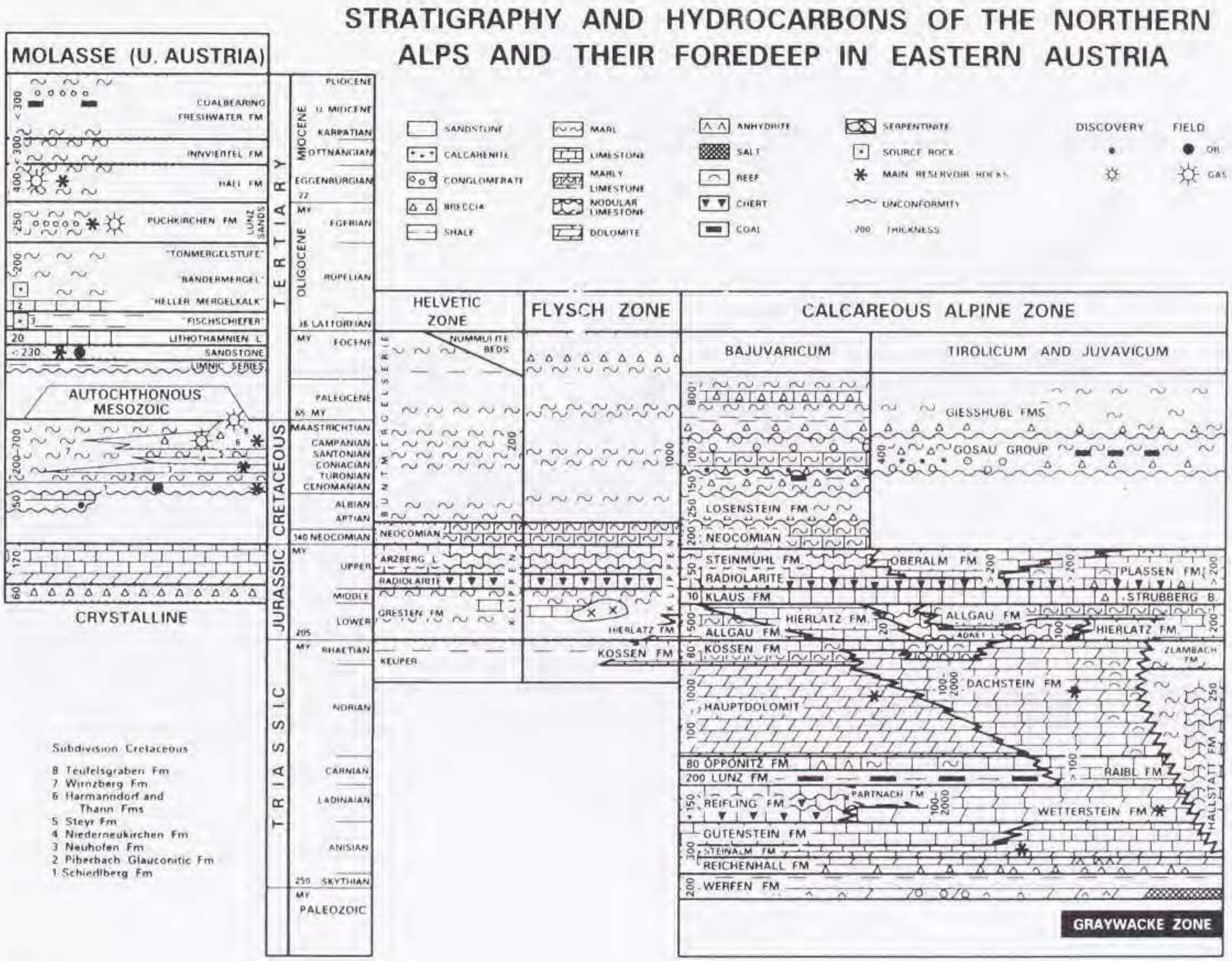

STRATIGRAPHY AND HYDROCARBONS OF THE NORTHERN ALPS AND THEIR FOREDEEP IN EASTERN AUSTRIA
MOLASSE (U. AUSTRIA)
COALBEARING FRESHWATER FM
INNVIERTEL FM
HALL FM
PUCHKIRCHEN FM
LUNZ SANDS
"TONMERGELSTUFE"
"BANDERMERGEL"
"HELLER MERGELKALK"
"FISCHSCHIEFER"
LITHOTHAMNIEN L.
SANDSTONE
LIMNIC SERIES
AUTOCHTHONOUS MESOZOIC
CRYSTALLINE
Subdivision Cretaceous
8 Teufelsgraben Fm
7 Wirnzberg Fm
6 Harmannsdorf and Thann Fms
5 Steyr Fm
4 Niederneukirchen Fm
3 Neuhofen Fm
2 Piberbach Glauconitic Fm
1 Schiedlberg Fm
TERTIARY
MIOCENE
OLIGOCENE
CRETACEOUS
JURASSIC
TRIASSIC
PLIOCENE
U. MIOCENE
KARPATIAN
OTTNANGIAN
EGGENBURGIAN
EGERIAN
RUPELIAN
LATTORFIAN
EOCENE
PALEOCENE
MAASTRICHTIAN
CAMPANIAN
SANTONIAN
CONIACIAN
TURONIAN
CENOMANIAN
ALBIAN
APTIAN
NEOCOMIAN
UPPER
MIDDLE
LOWER
RHAETIAN
NORIAN
CARNIAN
LADINIAN
ANISIAN
SKYTHIAN
PALEOZOIC
SANDSTONE
CALCARENITE
CONGLOMERATE
BRECCIA
SHALE
MARL
LIMESTONE
MARLY LIMESTONE
NODULAR LIMESTONE
DOLOMITE
ANHYDRITE
SALT
REEF
CHERT
COAL
SERPENTINITE
SOURCE ROCK
MAIN RESERVOIR ROCKS
UNCONFORMITY
200 THICKNESS
DISCOVERY
FIELD
OIL
GAS
HELVETIC ZONE
NUMMULITE BEDS
BUNTMERGELSERIE
NEOCOMIAN
ARZBERG L.
RADIOLARITE
GRESTEN FM
KEUPER
KLIPPEN
FLYSCH ZONE
HIERLATZ FM
KOSSEN FM
CALCAREOUS ALPINE ZONE
BAJUVARICUM
TIROLICUM AND JUVAVICUM
GIESSHUBL FMS
GOSAU GROUP
LOSENSTEIN FM
NEOCOMIAN
STEINMUHL FM
OBERALM FM
RADIOLARITE
PLASSEN FM
KLAUS FM
STRUBBERG B.
HIERLATZ FM
ALLGAU FM
ADNET L.
HIERLATZ FM
KOSSEN FM
ZLAMBACH FM
DACHSTEIN FM
HAUPTDOLOMIT
OPPONITZ FM
LUNZ FM
RAIBL FM
REIFLING FM
PARTNACH FM
WETTERSTEIN FM
HALLSTATT FM
GUTENSTEIN FM
STEINALM FM
REICHENHALL FM
WERFEN FM
GRAYWACKE ZONE

FIG. 7.

Within the Calc-Alpine units, potential structural traps were formed during their folding and thrusting. Unconformities, sealed by transgressive Late Cretaceous and Paleocene Gosau sediments, may provide for combination structural/stratigraphic traps (Fig. 9). Discovery of a number of oil and gas accumulations in Calc-Alpine units subcropping the Vienna basin has demonstrated that the potential of such structural and combined structural/stratigraphic traps (Kröll, 1980b). Hydrocarbon charge to such traps is provided by the autochthonous Oligocene Fish-shale west of the Bohemian basement spur and by basinal Late Jurassic shales in the Vienna Basin (Ladwein, 1988) and possibly also by source-rocks contained in the allochthonous units.

## EXPLORATION RESULTS

During the exploration of the Austrian Alps for hydrocarbons large gravity and magnetic surveys were carried out. Extensive surface geological mapping and structural analyses (Tollmann, 1976a, 1976b, 1985; Oberhauser, 1980) were followd by the acquisition of 5000 km of 2D reflection-seismic lines and the drilling of 32 exploration wells. In two areas 3D seismic surveys were recorded (Geutebrück et al., 1984).

In many areas the results of reflection-seismic surveys are not conclusive. Often the autochthonous section below the Alpine nappes gives rise to better and more continuous reflections than the allochthonous units. This is particularly true for areas where the latter are characterized by steep dips. However, in areas where the allochthonous units display relatively low dips, their internal configuration can be resolved by the seismic tool, as seen, for instance, on the line given in Fig. 8 which was recorded in the area of Salzburg (Kröll et al., 1981). The 3D survey over the gas/condensate field Höflein was very successful, despite difficult terrain, surface geological and environmental conditions; it involved the recording of an irregular grid using a mixed vibroseis and dynamite source.

Drilling activity involved the drilling of 24 exploratory wells in the Flysch Zone (16 ÖMV, 8 RAG) and 8 wells (ÖMV) in the Calcareous Alps. All wells drilled in the Flysch Zone bottomed in crystalline basement with some encountering an autochthonous Mesozoic sequence, albeit with variable thickness and of different composition. Of the 8 wells drilled in the Calcareous Alps, 4 wells bottomed in crystalline basement; of these, the wells Molln-1 and Grünau-1 penetrated a thick sequence of autochthonous Eocene and Mesozoic sediments (Fig. 4). The remaining four wells drilled in the Calcareous Alps terminated within allochthonous units. In the western Helvetic Zone of Voralberg, the well Au-1 was drilled to investigate the potential of the Jurassic sequence (see Fig. 1 and Encl. 1).

Exploration wells, which in combination with geophysical data, permitted to construct the series of structural cross-sections through the northern parts of the Alps, given in Encl. 1, are the Austrian wells Höflein-1 (Grün, 1984), Berndorf-1 (Wachtel and Wessely, 1981), Urmannsau-1 (Kröll and Wessely, 1967), Mittelbach-U1, Molln-1 and Grünau-1 (Wessely, 1988; Hamilton, 1989), Vordersee-1 (Geutebrück et al., 1984) and Vorarlberg Au-1 (Colins et al., 1990) and the German wells Vorderriss-1 (Bachmann and Müller, 1981) and Hindelang-1 (Müller et al., 1992).

According to the results of the well Berndorf-1, the nappe system of the Eastern Alps were transported during late Oligocene-early Miocene times northward over a distance of at least 40 km over the the autochthonous basement and its sedimentary cover. As such the autochthonous Mesozoic series and the lower part of the Tertiary fill of the Molasse Basin were protected from erosion. At the same time source-rocks were buried to sufficient depth to generate hydrocarbons whereas diagenetic processes accounted for a significant porosity and permeability reduction in reservoir rocks. The foreland basement dips very gently under the Calcareous Alps. The basement spur of the Bohemian Massif corresponds to an axial culmination.

The Flysch and Helvetic zones form thrust wedges in front of the Austroalpine nappes and thin out beneath them or are missing completely. Towards the West, the Helvetic Zone gains in thickness and becomes more complete. Serpentinites, encountered in the well Grünau, indicate

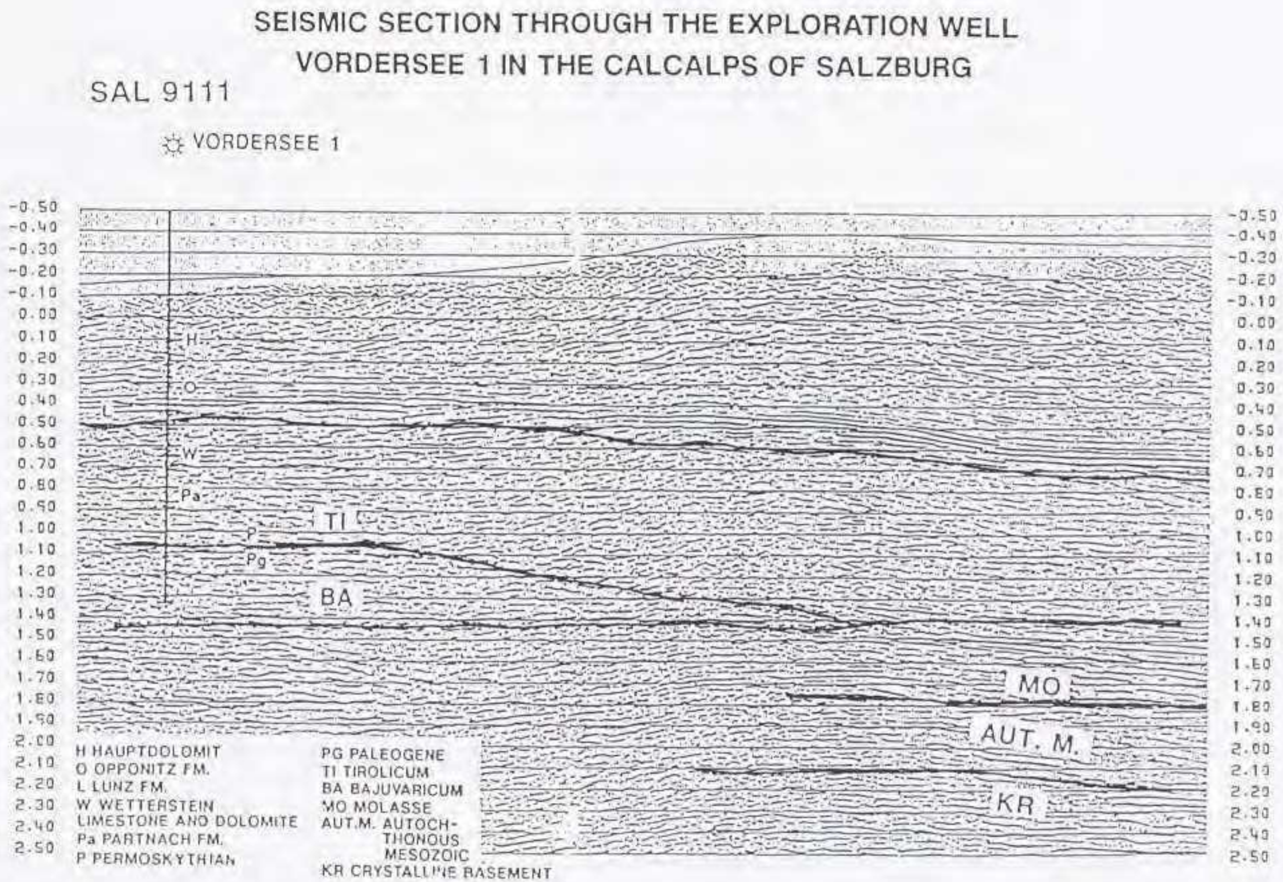



FIG. 8. For location of well Vordersee 1, see Fig 1. The well reached a total depth of 4264 m in the Bajuvaricum which thins to the south of the well.

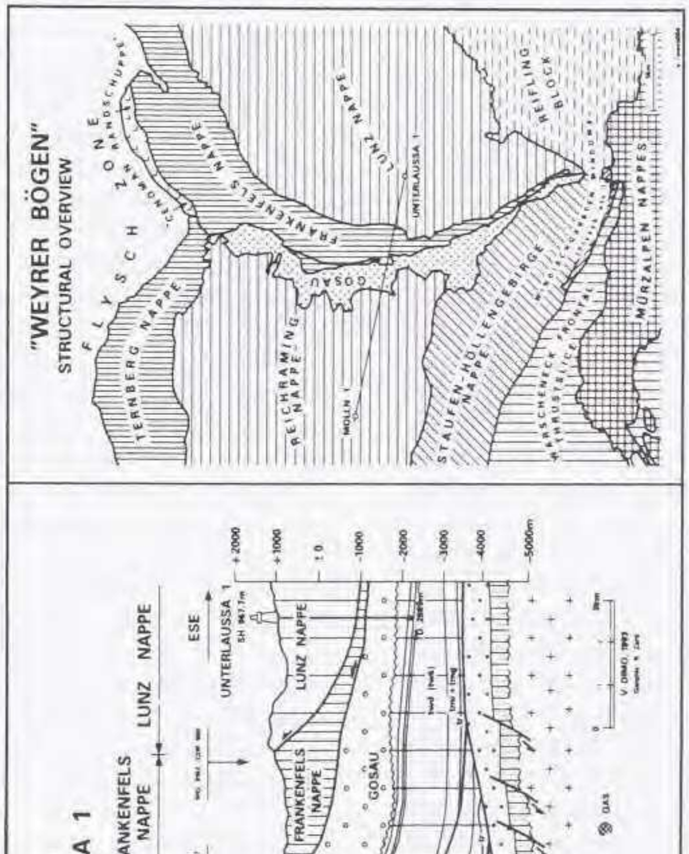



FIG. 9. for explanations see text

that the Flysch Zone is of North Penninic origin. In front of the Flysch Zone, the Molasse is folded and thrusted. This Sub-Alpine Molasse is involved in triangle zones in the West. On the Bohemian basement spur the Sub-Alpine Molasse forms a narrow belt, whereas towards the northeast, north of the Danube, the so-called Waschberg Zone consists of imbricated Molasse and Mesozoic series (Brix et al., 1977; Kröll, 1980a).

The Bajuvaricum, Tirolicum and Juvavicum units of the Calcareous Alps, which all form part of the Upper Austroalpine nappe system, display along strike dramatic changes in stratigraphic content, thickness and facies development and, consequently, in their structural style. Where Triassic platform carbonates are thin, folding plays a more important role than in areas of thick carbonates which are dominated by a relatively flat lying stacked thrust sheets.

The structural complexity of the Calcareous Alps is illustrated in Fig. 9 which crosses the "Weyrer Bögen" area, a transverse feature in the central parts of the Calcareous Alps. This structure originated by rotation, westward thrusting and duplication of two Bajuvaricum units. The lower, non rotated element is formed by the Ternberg and Reichraming nappes, corresponding to the upper, rotated element to the Frankenfels and Lunz nappes. A thick sequence of Cretaceous Gosau sediments, resting unconformably on the Reichraming nappe separates the latter from the Frankenfels and Lunz nappes. The well Unterlaussa-1 penetrated the Gosau sequence and encountered beneath it tight Triassic rocks of the Reichraming nappes. The objective of this well was to test a combined structural/stratigraphic prospect that is analogous to some of the gas accumulations occurring beneath the Vienna Basin. The neighbouring well Molln-1 encountered gas in the Reichraming nappe, thus proving the availability of hydrocarbons in the area.

## HYDROCARBON DISCOVERIES IN THE ALPS

The first oil was discovered in sub-thrust autochthonous Eocene sediments by the well Kirchham-1, drilled in the Flysch Zone of Upper Austria. A much larger, and commercially exploitable accumulation is the Höflein gas/condensate field located near Vienna which contains ultimate recoverable reserves of some $7 \cdot 10^9$ $m^3$ (250 BCF) This field is contained in autochthonous Middle Jurassic dolomitic and cherty sandstone and deltaic sandstones (Sauer et al., 1992) involved in a horst block which was overridden by Flysch nappes (Encl. 1). Reservoir pressures are hydrostatic; the gas contains a low percentage of $CO_2$.

Grünau-1 was the first well spudded in the Calcareous Alpine nappes which encountered an autochthonous Mesozoic sequence and discovered at a depth of more than 4800 m light oil in overpressured Early Cretaceous sandstones (Fig. 4). Initial flow rates of more than 750 bbls/day declined, however, rapidly and the well was abandoned. Similarly, the well Kirchdorf-1, drilled north of Grünau-1, tested uncommercial quantities of oil.

Within the Sub-Alpine Molasse of Upper Austria, the well Mühlreit-1, drilled by RAG, produced considerable amounts of oil from overpressured Oligocene sandstones before being abandoned. In the Helvetic Zone of Vorarlberg, several intervals of Middle Jurassic sandstones and Late Jurassic carbonates yielded on test only gas shows and salt water. For instance, the German well Hindelang-1, which penetrated a long section within the Helvetic Zone, tested from a 300 m interval in the Early Cretaceous Schrattenkalk gas at flow rates of 3.7 MMCFF/day; after prolonged testing also this well was abandoned.

In well Urmannsau-1, located in the Calcareous Alps of Lower Austria, many oil shows were observed; however, on test fractured Middle Triassic dolomites yielded only salt water. Whether this reservoir is oil bearing at a structurally higher location is unknown.

The well Vordersee-1, drilled southeast of Salzburg in the more simply structured part of the Calcareous Alps, tested from Middle Triassic dolomites, sealed by the shales and tight sandstones of the Lunz formation, salt water only.

In contrast, the well Berndorf-1, drilled near the western border of the Vienna Basin, penetrated a very thick, complex sequence of Middle and Late Triassic carbonates from which fresh water with a maximum temperature of 45°C was tested down to a depth of 4500 m. In combination with formation water analyses from the Vienna Basin, this indicates that meteoric waters can penetrate to great depths in the Calcareous Alps, setting up a complex and very active hydrodynamic system.

## CONCLUSIONS

A distinction has to be made between the sub-thrust autochthonous play and plays aimed at allochthonous prospects.

Sub-thrust autochthonous prospects are located in a depth range of 3000 to more than 6000 m. This play has to contend with a distinct reservoir risk, both in terms of the presence or absence of Mesozoic and Eocene objectives and, with increasing depth rapidly deteriorating reservoir characteristics. However, suitable seals and trapping conditions are available. Hydrocarbon charge appears to be assured, although under the deeper parts of the Calcareous Alps prospects are likely to be gas prone. High formation pressures are common and there is little chance for reservoir flushing. A further risk factor is the reflection-seismic definition of drillable structures. In this respect, a complex overburden velocity structure provides for depth conversion uncertainties and thus impedes the definition of closure of predominantly low relief extensional structures; moreover, topographic constraints on recording dense enough grids are severe in the Calcareous Alps. In view of the above the Sub-Alpine Molasse, the Flysch Zone and the frontal parts of the of the Calcareous Alps must be regarded as more prospective than the interior parts of the latter where drilling cost are very high. This is born out by the discovery of the Höflein field in the Flysch Zone and the results of the well Grünau-1 drilled near the northern margin of the Calcareous Alps. The objective of future exploration is to locate relatively high relief structures having a large trap volume which, in case of success, could justify economic field development .

Allochthonous plays have to contend in many areas with good reservoir conditions but with a poor seal and trap potential. Seal and trapping conditions are thought to improve towards the frontal and deeper parts of the Calcareous Alps. Hydrocarbon charge is provided by mature autochthonous source-rocks and possibly by source-rocks contained in the allochthonous units. Thick carbonate series can be characterized by very active hydrodynamic regimes involving meteoric waters; this could prohibit the accumulation of commercial quantities of hydrocarbons. In areas of near surface steep dips, seismic resolution is poor. However, although in area of relatively gentle dips seismic resolution is adequate to define structures at deeper levels, which may be protected from meteoric water circulation, the rugged topography often prohibits the recording of dense enough grids to establish 3-way closure of potentially prospective structures. Surface geological information and the construction of balanced cross-sections may go some way to resolve the structural complexity of the Alpine allochthon. However, in the face of objective depths in the range of 4000 to 5000 m and high drilling cost, prospects must be adequately defined before their evaluation by the drill can be justified. The discovery of significant oil and gas accumulation in the allochthonous units forming the substratum of the Vienna Basin, highlight the potential of this play. Similarly, results of the well Hindelang-1 are encouraging for exploration of the Helvetic zones.

Past exploration of the Austrian Alpine belt was rewarded with only limited success due to poor structural definition of prospects involving either autochthonous or allochthonous series. Although all ingredients for a successful exploration play appear to exist, at least in some parts of the Austrian Alps (Table 1), the risk/reward ration must be considered as lop-sided under todays oil and gas price scenario.

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Exploration Criteria in Alpine Thrust and Subthrust Areas

| | Allochthonous | | Autochthonous |
|---|---|---|---|
| | Calcareous Alps | Helveticum, Molasse | |
| Reservoir | fair | poor | poor to fair |
| Seal | poor | fair | fair |
| Trap | poor | fair | fair |
| Hydrocarbons | gas/condensate, oil. Toward south generation limit | | |
| Pressure | normal | high to normal | mostly high |
| Seismic quality | mostly poor | fair to poor | fair to poor |
| Drilling frequency | very low | low | very low |
| Drilling depths | 2000 - 5000 m | 3000 - 5000 m | 5000 - 7000 m |
| Drilling costs | moderate to high | moderate to high | very high |

TABLE 1

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**Enclosure**

Encl. 1 Regional cross-sections through Flysch-Kalkalpen